THE NEW MILLENNIUM SEPARATED SPACECRAFT INTERFEROMETER

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Abstract

Spaceborne optical interferometry has been identified as a critical technology for many of NASA's 21st century science visions. Included in the visions are interferometers that can probe the origins of stars and galaxies, and can ultimately study Earth-like planets around nearby stars. To accomplish this feat, separation of an interferometer's small collecting apertures by large baselines are required - hundreds of meters up to thousands of kilometers. Thus the large separations require multiple spacecraft formation flying. Furthermore, optical pathlengths over these distances must be controlled to the nanometer level. This level of control demands tightly coupled spacecraft controls, active optics, metrology, and starlight detection technologies. To date, these technologies have been demonstrated only in ground applications with baselines of order of a hundred meters; space operation will require a significant capability enhancement. This paper describes the New Millennium separated spacecraft optical interferometer mission concept and technologies. The mission is designed to provide a technology demonstration for tightly coupled multiple spacecraft formations and very long baseline optical interferometry. The interferometer would be distributed over three small spacecraft: two spacecraft would serve as collectors, directing starlight toward a third spacecraft which would combine the light and perform the interferometric detection. The interferometer baselines would variable, allowing baselines of 100 m to 1 km in an equilateral formation, to provide angular resolutions from 5 to 0.5 nanoradian (1 to 0.1 milliarcsec).

INTRODUCTION

Many scientific goals of the 21st century in the fields of astronomy and astrophysics require order-of-magnitude advancements in optical angular resolution. Angular resolution improves linearly with the diameter of filled-aperture telescopes, or in the case of interferometers, with the distance (baseline) between widely separated apertures. Interferometers with baselines of 100 meters are being implemented on the ground, offering high (5 nanoradian or 1 milliarcsec) resolution of compact astrophysical objects. Many of these objects, however, are faint and can only be detected by taking advantage of the enormous increase in sensitivity afforded by space-based observation, beyond the turbulent and partially opaque atmosphere. Among the key scientific goals enabled by space-based optical interferometry are submilliarcsec measurement of stellar diameters, resolution of close and interacting binaries, detection of extra-solar planets, and precise measurement of galactic and cosmic distance scales.

Optical interferometers collect light at widely separated apertures and direct this light to a central combining location where the two light beams are interfered. Fringes produced by the interference provide magnitude and phase information from which a synthesized image can be generated. Space-based optical interferometers can be implemented as single monolithic spacecraft, in which small (0.1 m to 0.3 m) collecting apertures are separated by tens of meters, or implemented as separated spacecraft where baselines of hundreds, or even thousands, of meters enable measurement with very high (sub-milliarcsec) angular resolution. A separated spacecraft optical interferometer concept, referred to as the New Millennium Interferometer (NMI), is a simplified interferometer that demonstrates enabling technologies while still retaining science capabilities. It has been identified as a strong candidate for one of the New Millennium deep space technology demonstration mission in preparation for a separated spacecraft implementation of the Terrestrial Planet Finder mission and other future exoplanet imaging and high resolution astrophysics formation missions.

MISSION DESCRIPTION

The NMI consists of three separated spacecraft forming an equilateral triangle, as shown in Figure 1. Two collector spacecraft direct stellar light to a third combiner spacecraft where the light beams are combined for interferometric measurements. NMI will image bright astrophysical objects (14th magnitude) in the visible at 0.55 to 0.9 microns, with a 100 m to 1 km baseline to attain an angular resolution of 5 to 0.5 nanoradian (1 to 0.1 milliarcsec).

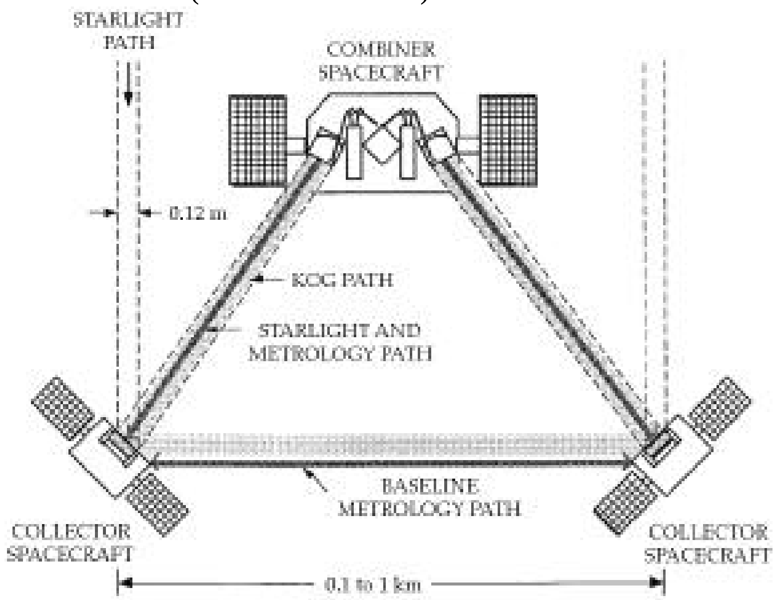

FIGURE 1. New Millennium Interferometer Concept.

All three NMI spacecraft will be launched from a single launch vehicle to a heliocentric orbit. After launch, the individual spacecraft are released and deployed into formation. The formation will be deployed up to 1 km, as permitted by diffraction at the metrology apertures; the baseline can be reduced to 100 m by scaling down the constellation triangle. The propulsion system is used for formation flying to ±0.01 m (1 cm) in three transitional axes and to point each spacecraft to ±0.3 milliradian (1 arcminute) relative to one another. Fuel mass is sized to allow for 1000-0.1 radian (6-degree) maneuvers at a 100 m baseline, which was the simplified metric used for computations. Two propulsion systems are currently under consideration. The baseline design uses 4.5 mN cold gas (GN_2) thrusters, with 15 kg of propellant to meet the mission needs. An alternate design explores the use of electric propulsion. At a 6 Hz firing rate, the Pulsed Plasma Thruster (PPT) provides 4.2 mN thrust, requiring only 1 kg of Teflon propellant due to an inherently higher specific impulse (I_{sp}).

TECHNOLOGY DESCRIPTION

The principal technologies required to perform separated spacecraft optical interferometry for NMI are formation flying, starlight subsystem, laser metrology, and interferometer phasing. Formation flying employs advanced controls and an innovative sensor which uses GPS technology (Lau, et al. 1996) for deep space. The starlight subsystem is similar to those used in ground interferometers (Shao, et al. 1988 and Colavita, et al. 1994), incorporating fast steering mirrors and optical delay lines for high bandwidth tilt and pathlength control. Laser metrology among the spacecraft provides equivalent structural rigidization similar to the approach for monolithic space interferometers (Shao, et al. 1995). Phasing of the interferometer uses a Kilometric Optical Gyro (KOG), which is a Sagnac interferometer employing counter-propagating laser beams among the three spacecraft.

Formation Flying

The design approach for NMI is to minimize the instrument to spacecraft interactions. The high bandwidth fine pointing and phasing control is provided by the instrument, with a dynamic range such that closed-loop spacecraft control is not needed. There is nominally no feedback between the interferometer internal control system and the spacecraft control system.

NMI requires spacecraft formation flying accuracy to ±0.01 m and ±0.3 milliradian to avoid saturation of the optical delay lines and collector flat mirror gimbals respectively. However, precision formation flying also provides: 1) baseline orientation changes, to rotate the instrument about the line-of-sight, sweeping out a chord in the (u,v) plane; 2) change in formation size, to vary the angular resolution; and 3) retargeting the interferometer to point at other objects. Innovative advanced formation controls, such as cooperative, centralized, distributed and biological controls, will be examined for NMI.

Also key to formation flying is formation sensing of inter-spacecraft relative distances and angles. An innovative sensor concept, based on JPL TurboRogue™ GPS receiver technology, was developed for this and other applications (Lau, et al. 1996). The Autonomous Formation Flying sensor (AFF) uses GPS-like signaling among multi-channel transceivers on the three spacecraft. Each spacecraft transmits a carrier and pseudorange signal which is received by multiple antennas on the other spacecraft. Multiple patch antennas on each spacecraft allows for both 4π steradian angular coverage as well as determination of relative angle and range. The accuracy for the AFF is ±0.01 m relative distance and ±0.3 milliradian relative angle, consistent with the formation-flying requirements.

Starlight Subsystem

The starlight subsystem begins with a flat mirror on each of the two collector spacecraft. Each directs a 0.12 m diameter beam of stellar light to the combiner, as shown in Figure 1, with corner-cube retroreflectors located at the center for use by the laser metrology system. Each mirror is mounted on a three-axis gimbal (tip, tilt and roll) with range to accommodate a ±0.09 milliradian (0.005 degree) spacecraft attitude deadband. Flat mirrors were selected for simplicity, allowing uniform array expansion when interspacecraft distances are increased. For a larger system a better approach is for the collector optics to produce a beam waist at the combiner spacecraft, so that only a single large optical element is required. This latter approach mandates a fixed collector to combiner separation, unless the curvature of the collector mirrors is made variable.

Figure 2 shows a concept for the beam combiner in the combiner spacecraft that is similar to systems used in ground interferometers. Section A illustrates the starlight optics on the combiner spacecraft: the collector starlight enters a beam compressor (a pair of off-axis confocal parabolas with 0.13 m clear aperture) and compresses it to 0.03 m beams. The compressed beam is redirected by the fast-steering mirror (FSM), which provide high-bandwidth tilt control, onto an optical delay line (ODL), and then to the beam combiner. Starlight from the second collector spacecraft follows a symmetric optical path to the beam combiner, as shown in Section C. The ODL are used in each arm for fine pathlength control. A range in delay of 0.02 m with nanometer resolution accommodates the formation-flying deadband without the need for nanometer control of spacecraft position. The short delay-line range allows simplification by using of a two-stage (piezoelectric transducer (PZT)/voice-coil) system. Closed-loop pathlength control to less than 10 nm is routinely accomplished with ground versions of similar delay lines and is baselined for NMI.

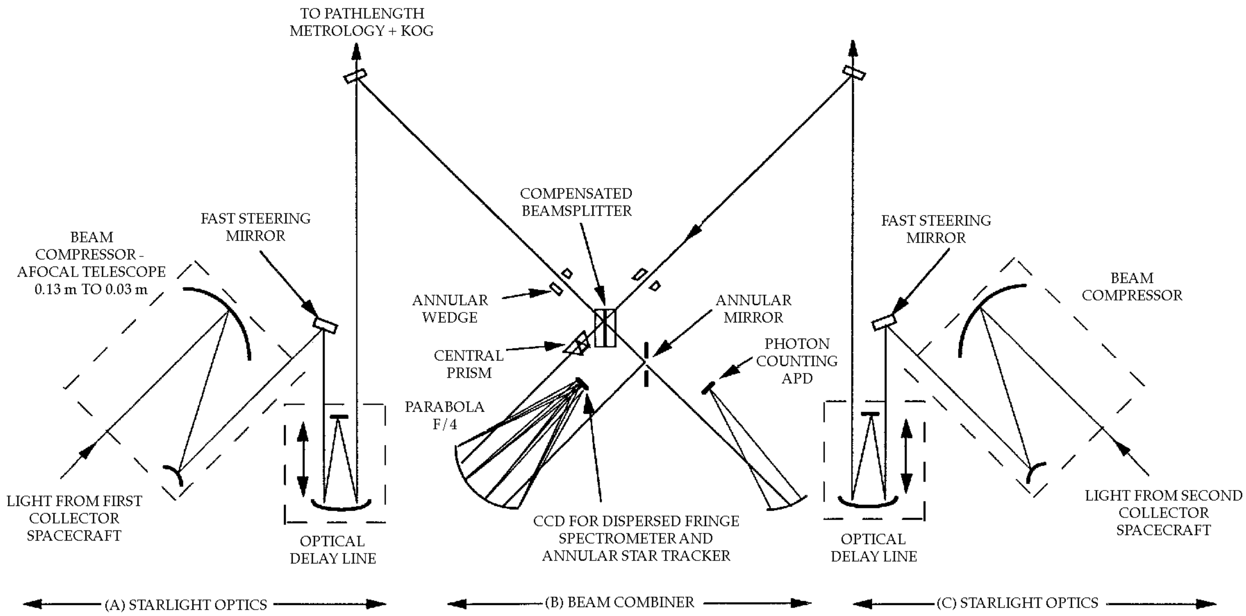

FIGURE 2. NMI Starlight Subsystem.

Section B shows a concept for the interferometer beamsplitter and fringe-detection back end. The two outputs of a compensated beamsplitter feed different detectors: a photon-counting avalanche photodiode (APD) detector for high sensitivity fringe detection (for science), and a fast-framing Charge Coupled Device (CCD) (for fine guiding). The pupil of the beamsplitter output feeding the CCD is divided spatially between fringe sensing and tilt sensing. The inner part of the beam passes through a direct-view prism, providing a dispersed fringe pattern on one line of the CCD. The annular portion of the beam is non-dispersed, providing images of the two input pupils on the CCD. Annular wedge prisms in each arm offset the images from each other and from the dispersed fringe, allowing the same CCD to serve for both tilt sensing and fringe detection. Also shown in Figure 2 is the injection of the pathlength metrology and KOG, discussed is later sections. The ultimate sensitivity of the system is estimated as 14 magnitude, limited by the coherence time provided by the KOG.

Laser Metrology

The absence of a structure means that structural rigidity is achieved actively, rather than through reliance on the intrinsic stiffness of a truss. The sensors for achieving rigidity are the laser metrology systems which measure precise inter-spacecraft distances and interferometer component positions. As shown in Figure 2, laser metrology is introduced into the starlight path through a dichroic beamsplitter in the beam combiner, and measures the distance from the combiner to the corner cubes at the center of each collector’s flat mirror. The third laser path is implemented separately between the two collector spacecraft where separate corner cubes (from the ones on the gimbal mirrors) can be used for this measurement. With these three metrology beams, the positions of the spacecraft can be controlled to the nanometer level to stabilize the interferometer. It is however more efficient to use the data for feedforward control to the optical delay lines for stabilizing the starlight path. This would correct for both baseline changes as well as internal pathlength changes. The delay-line range (0.02 m) establishes the required accuracy of the stationkeeping of the individual spacecraft based on the implementation that there is no feedback between the delay-line control system and the spacecraft control system. Alternatively, with tighter systems coupling, the delay-line range could be reduced.

The metrology system would use heterodyne techniques which readily provide much better than 10 nm position accuracy. The laser source would nominally be a single-frequency device to provide a narrow linewidth in order to maintain coherence over the 2 km maximum round-trip propagation. Heterodyne implementation would use fiber-fed frequency shifters to provide the necessary frequency offset between polarizations.

Finally, two other metrology beams are used internal to the combiner spacecraft. These monitor the ODL positions in order to separate delay-line position changes from spacecraft position changes.

Kilometric Optical Gyro

The conventional approach to point the interferometer formation so as to not to blur the fringe requires off-axis stars for sensing. However, it would be problematic with long baselines for two reasons. A small off-axis angle translates into a large delay change: 14.6 microradian (3 arcminute) over a kilometer baseline is 1 meter of path delay, which is not easily accommodated with the NMI structure. In fact with the simple collector mirrors, the light would miss the combiner entirely. Thus accommodating off-axis stars would require increases in complexity for both the collector and combiner spacecraft. The other reason that off-axis guide stars are problematic is because when long baselines resolve the nearby bright sources that would ordinarily serve as guide stars, it reduces the available signal-to-noise ratio for tracking.

An alternative approach is to use an inertial sensor. The long baselines of NMI allow for the use of a Kilometric Optical Gyro (KOG). The KOG is a Sagnac interferometer employing counter-propagating beams among the three spacecraft - essentially a fiber-optic gyro where the fiber sensing coil is replaced by space, shown schematically in Figure 3. The KOG measures provides formation rotation sensing at a high frequency. It is a particularly good match to the long baselines of a separated-spacecraft interferometer, as the sensitivity of the KOG is proportional to the enclosed area. The required pointing accuracy also scales with baseline, so that the KOG works better with long baselines.

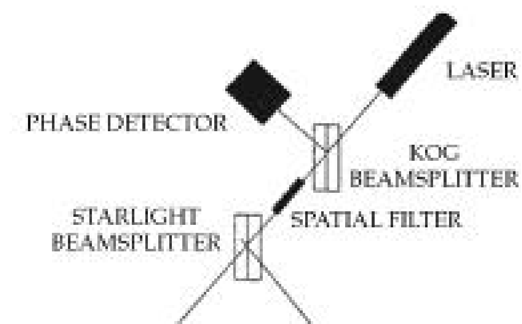

FIGURE 3. Kilometric Optical Gyro Concept.

During the mission, by monitoring separately the length of the individual legs of the triangle, it is possible to separate rotation from length change. This is the purpose for the ODL metrology system described in a previous section. While it is not needed for control reasons, subtraction of this measurement from the combiner to collector metrology can provide a precise measure of just the inter-spacecraft distance. The KOG beam is injected through a dichroic beamsplitter in the beam combiner (Figure 2), and propagates toward each collector. To reflect the KOG light around the loop of spacecraft, rather than back toward the stellar source, a diffraction grating is placed on the collector mirrors. The grating is nominally implemented as a second-surface grating, with the first surface coating a dichroic to reflect starlight and transmit the KOG light. Pointing of the grating is accomplished using the roll axis of starlight gimbal. The gimbal is sensed using edge- and angle-sensors around the boundary. The KOG would nominally operate at 1.5 microns, distinct from the starlight and laser-metrology wavelengths. The implementation of the KOG may be able to use a modified fiber-optic gyro sensor head, with changes to the internal electronics to accommodate changing loop pathlengths.

CONCLUSION

The NMI concept is a simplified separated spacecraft interferometer with the goal of technology demonstration to enable future applications of interferometer and other multiple spacecraft formations. Key technologies presented for general space interferometry included starlight subsytem and laser metrology. Technologies for general formation flying spacecraft included formation controls, formation sensing and inertia phasing of formations.

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